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Carbon emission reduction potential of rural energy in China

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ABSTRACT

With the largest population living in countryside, the carbon dioxide (CO_2) emission from rural energy consumption is a serious problem in China. The full development and utilization of renewable energy is the key and effective way for solving the CO_2 emissions problem. This paper reviews the rural energy consumption level and structure in China. Then, this paper discusses the potential for renewable energy development as well as its CO_2 emissions reductions in rural areas. Results show that if full development and utilization of renewable energy is achieved, on the basis of energy data in 2008, China's rural energy consumption and even 2.2 times of that can be supplied by 100% carbon-free energy resources (which do not contain the biomass energy) without considering economic and technical constraints, and 2.4 times of that can be provided by renewable energy. Moreover, to evaluate the application priority, cost-effectiveness of each renewable energy resource is analyzed. Based on the characteristics of renewable energy resources, new promotional strategies to ensure the full development and utilization of renewable energy in rural China are also presented.

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1. Introduction

Energy saving and emission reduction, the key to developing a circular economy and protecting the ecological environment, have become the focus in the world, along with which many low carbon energy scenarios such as Global Energy Assessment (GEA) [1] and Energy Technology Perspectives 2012 (ETP2012) [2] are continuously emerging. The GEA provides technical guidance for governments and intergovernmental organizations to develop pathways for sustainable development of energy and reductions of greenhouse gas (GHG). In the ETP2012, global scenarios and strategies to a sustainable energy system in 2050 are laid out. As a kingdom of Carbon Trade, China faces great challenges in providing pathway for emissions reductions. Since 2006, China's CO_2 emission has raced ahead of the United States and gone into the first place [3]. As the largest emitter of CO_2 in the world, China has established the target that by 2020, CO_2 emissions per unit of GDP would be decreased by 40–45% of 2005 levels [4,5]. The unprecedented pressure on reducing CO_2 emissions brings huge challenges to China [6]. As a large agricultural country, the rural areas play vital roles in reducing CO_2 emissions in China [7].

With China's rapid economic development, the demand for energy is increasing at a great rate. As shown in Table 1, from 2000 to 2008, China's total energy consumption rose from 967 to 2007 million tonnes of oil equivalent, which is equal to 1383 to 2867 million tonnes of standard coal equivalent (Mtce). In the meantime, China's rural energy consumption also showed a rapid growth, whose total amount had increased substantially from 672 Mtce to 925 Mtce [8]. Therefore, to achieve the CO_2 emission reduction target, energy saving and emission reduction in rural China is of vital importance. The analyses of rural energy issues in China have been booming [9]. Rural energy consumption, as a primary source of China's GHG emissions, is an important aspect in reducing China's CO_2 emissions. China, as an agricultural country with vast rural territory and huge rural population (more than half of the nation's population), has abundant renewable energy resources in rural areas. However, at present the rural energy consumption, for the most part, is still mainly composed of the low-efficiency and higher carbon-content fuels such as coal, firewood, straw and coal. The high-quality modern renewable energy resources only occupy a low proportion. This kind of energy consumption structure intensifies the CO_2 emissions and brings negative influence to environment [10,11]. Thus, in order to solve the emissions issue, we should focus more on optimizing the rural energy consumption structure and developing renewable energy.

There are many related studies on China's rural energy consumption, such as its affecting factors, consumption pattern, relevant energy policy and sustainable development [12–14]. The previous rural energy studies presented a general idea of the rural energy consumption, however the specific way to promote emissions reductions still needs further studies. Thus, the low carbon development of China's rural energy certainly requires an in-depth, comprehensive study. Rural China has extremely rich renewable energy resources such as biomass, solar, wind, geothermal and small hydropower. Low carbon development for rural energy, the key is making full development and utilization of renewable energy resources. That is to say, it is necessary to construct a new rural energy consumption structure whose main components are renewable energy resources. To develop effective ways to guide sustainable energy system and solve CO_2 emissions problem, the analysis of development potential is essential. Hence, combining with the distribution and characteristics of China's rural renewable energy resources, the potentiality of exploitation and utilization of renewable energy, as well as its potential for reducing CO_2 emissions under ideal conditions is analyzed. In addition, the popularization and application priority of renewable energy resources are also analyzed and discussed in this study.

Table 1
The total energy consumption from 1990 to 2008 all over the world, in million tonnes of oil equivalent.

	1990	1995	2000	2005	2008	Rate of change
China	685	917	967	1572	2007	193%
India	181	236	295	362	441	144%
Japan	431	489	510	520	509	18%
Korea	90	147	189	222	236	162%
Taiwan	50	66	94	109	109	118%
Russia	862	658	614	649	681	−21%
South Africa	90	100	107	119	131	46%
Canada	251	277	300	323	335	33%
Brazil	124	150	183	198	228	84%
United States	1963	2117	2310	2342	2302	17%
Germany	349	332	329	324	310	−11%
France	218	235	254	260	255	17%
England	211	214	223	225	211	0%
The World	8097	8545	9260	10565	11315	40%

Data comes from BP statistical review of world energy.

2. Rural energy consumption levels and structures in China

As shown in introduction, from 2000 to 2008, the total energy consumption of rural China has increased greatly, which is from 672 to 925 Mtce [8]. Correspondingly, per capita energy consumption has increased from 830 kg standard coal equivalent (kgce) in 2000 to 1310 kgce in 2008. However, from an overall perspective, the energy consumption structure in rural China is still traditional, which mainly consists of traditional energy such as coal, firewood, and straw burned directly with low efficiency, while the renewable energy resources account for only a tiny share. On the basis of the energy consumption data of 2008, the energy consumption structure and CO_2 emissions in rural China are analyzed first in this paper.

2.1. Energy consumption structure

The energy consumption in rural China of 2008 is 925 Mtce, among which the resident energy consumption and production energy consumption accounted for 63% and 37%, respectively [8]. The production consumption refers to the energy consumption which is used for agricultural production as well as its processing such as animal production, agricultural irrigation, crops cultivation, agricultural product processing and so on. As shown in Fig. 1, the energy consumption in rural China is still mainly consisted of

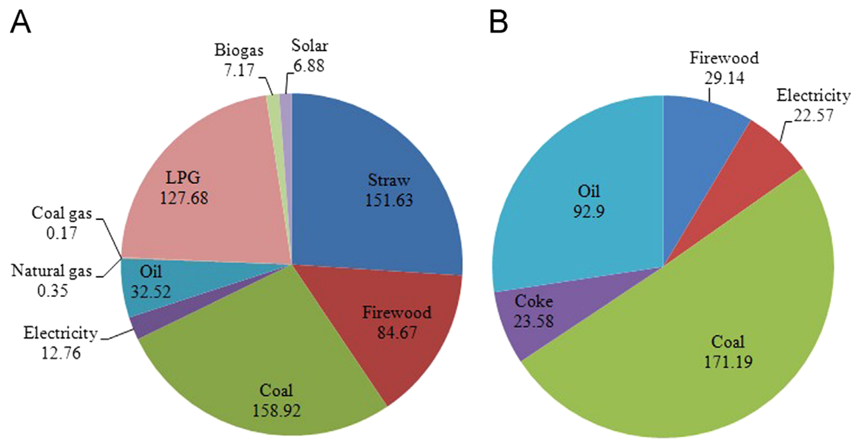

Fig. 1. Energy consumption structure of rural China in 2008, Mtce. (A) Resident energy consumption and (B) production energy consumption.

Table 2
CO_2 emission coefficients of different energy, in tCO_2/tce.

Energy	CO_2 emission coefficients
Coal	2.689
Oil	2.042
Electricity	8.115
Coke	3.136
LPG	1.747
Natural gas	1.721
Coal gas	1.368
Straw	2.494
Firewood	2.484
Biogas	1.641

Table 3
CO_2 emissions of energy consumption in rural China 2008.

Residential			Production		
Energy	CO_2 emissions (Mt)	Proportion (%)	Energy	CO_2 emissions (Mt)	Proportion (%)
Straw	378.17	26.60	Firewood	72.38	7.39
Firewood	210.32	14.80	Electricity	183.16	18.70
Coal	427.34	30.06	Coal	460.33	47.00
Electricity	103.55	7.28	Coke	73.95	7.55
Oil	66.41	4.67	Oil	189.70	19.37
Natural gas	0.60	0.04	Total	979.52	100
Oil gas	0.23	0.02			
LPG	223.06	15.69			
Biogas	11.77	0.83			
Solar	–	–			
Total	1421.43	100			

Table 4
Potential of modern biomass energy.

Biogas (10^8 m^3)		Bio-liquid fuel (Mtce)	Biomass power generation (Mtce)
Fermentation of straw	Livestock breeding		
800	700	70.00	73.69

the fuels with higher carbon content such as coal and traditional biomass (e.g. firewood, straw), and the development of renewable energy is still very low.

Table 5
Housing roof area in China.

Roof area in China (10^2 km^2)			
Housing roof area in urban	22.0	Housing roof area in rural	156.0
Area of PVs application in urban	11.0	Area of PVs application in rural	78.0
Eastern of urban China	7.0	Eastern of rural China	32.0
Central of urban China	2.6	Central of rural China	28.0
Western of urban China	1.4	Western of rural China	18.0

Data comes from China National Engineering Research Center for Human Settlements

Table 6
PV integrated into buildings in rural China.

Contents		East	Center	West
Annual generating hours		1500	1400	1600
Capacity (Gwp)		384	336	216
Annual electricity generation	Electricity (10^2 GWh)	5760	4704	3456
	Standard Coal (Mtce)	232.70	190.04	139.62
	Total (Mtce)	562.36		

2.2. *Carbon dioxide emissions*

According to the IPCC Guidelines for National Greenhouse Gas Inventories [15] and relevant references [8,16,17], the carbon emission coefficients of different energies are obtained through converting (Table 2).

Based on the energy consumption in rural China 2008 (Fig. 1), we can get the CO_2 emissions (Table 3 and 4) by combining with the CO_2 emission coefficients of different energies (Table 2).

3. Potentiality of renewable energy sources in rural China

Rural China enjoys abundant renewable energy resources, including biomass, solar, geothermal, wind and small hydropower, while they are still very rarely developed and exploited.

3.1. *The potentiality of biomass energy*

Rural China's biomass resources are pretty abundant, thus there is great potentiality for the development and utilization of modern biomass energy such as biogas, bio-liquid fuel and biomass power generation.

Table 7
Area of the desert in China, 10^4 km^2.

Province	Area	Desert	Gobi
Sinkiang	71.3	42.0	29
Gansu	6.8	1.9	4.9
Qinghai	7.5	3.8	3.7
Inner Mongolia	40.1	21.3	18.8
Ningxia	0.65	0.4	0.25
Jilin	0.36	0.36	0.0
Liaoning	0.17	0.17	0.0
Shaanxi	1.1	1.1	0.0
Heilongjiang	0.26	0.26	0.0
Total	128.24	71.39	56.95

Table 8
Development potential of solar thermal systems.

Contents	Solar water heater (10^4 m^2)	Solar heating building (10^4 m^2)	Solar cooker (10^4 units)
Utilization situation in 2008	4758.7	1590.5	135.7
Substitution of standard coal, 10^4 tce	713.8	47.7	43.2
Ideal conditions	68,128	780,000	2270.9
Substitution of standard coal, 10^4 tce	10,219.13	23,392.64	722.94

3.1.1. Development potential of biogas

In China, there are about 300 Mt of crop straws can be used as energy resources per year [18]. With the relevant policies, the proportion of modern biomass and traditional biomass can be raised to 2:1, namely there is 200 Mt of straw available for developing biogas. Some relevant studies show that 2.5 kg of straw can produce biogas of 1 m^3 (m^3) [19,20]. Hence, the total annual production of straw in rural China could generate around 8.0×10^{10} m^3 of biogas.

According to the statistics by Chinese Ministry of Agriculture, there are about 1120 Mt of animal wastes from the national large-scale livestock breeding, which can be used to produce biogas about 2.0×10^{10} m^3. In addition, there are about 1.48×10^8 breeding farmers among the decentralized livestock which are suitable for developing biogas, and the potential production of biogas is more than 5.0×10^{10} m^3 [21]. Hence, biogas produced by the animal wastes is equivalent to 7.0×10^{10} m^3.

In conclusion, the total annual production of biogas can reach 1.5×10^{11} m^3, which is equivalent to 107 Mtce.

3.1.2. Development potential of bio-liquid fuel

The area available for planting energy crops such as sugarcane, sweet sorghum, manioc, sweet potatoes, Tung tree, and Pistacia can meet the demand of 50 Mt of bio-liquid fuel raw materials [16] —equivalent to 70 Mtce.

3.1.3. Development potential of biomass power generation

There is about 300 Mt of forestry waste that is available for energy production [18], therefore the total installed capacity of biomass power can reach 24 GW. It is estimated that the available hours for generating can reach 7600 h each year, so the annual electricity production is expected to reach 182.4 TW h, equaling to 73.69 Mtce (the standard coal coefficient of electricity is considered as 0.404 kgce/kW h).

3.2. The potentiality of solar energy

From 1971 to 2000, the 30 yr average data suggested that China possesses more than 96% of the country area with abundant solar energy resources, whose annual solar radiation quantity is about 1052–2450 kW h/(m^{2}a). The solar energy resource has obvious zone distribution characteristic in China [22]. According to the solar energy radiation quantity, the solar energy zones can be divided into four types: extremely abundant area, very abundant area, abundant area and normal area, which account for 17.4%, 42.7%, 36.3% and 3.6%, respectively [23].

3.2.1. Solar energy used in electric systems

(1) Building-integrated PV
At present, there are more than 70% solar cells connected to the grid all over the world [24]. In China, the PV systems are mainly integrated into urban building. However, rural China possesses more housing roof than urban (shown in Table 5), which reaches 7800 km^2 [25]. The development potential of solar energy utilization integrated into buildings in rural China is shown in Table 6, whose annual electricity generation is the product of annual generating hours and capacity.

(2) Desert power station
China is blessed with abundant untapped solar resources, particularly in the western region where cannot be used for farming, such as desert and Gobi, with an area of 1.28×10^6 km^2 (shown in Table 7). The annual sunshine time and solar radiations of the desert possessing abundant solar energy resources are more than 2000 h and 1.6 MW h/m^2, respectively. Taking efficiency into account, we assume that 1% of the desert region is used to set up the desert power station. The installed capacity of station is approximately 100 MWp/km^2 [26], so the potential total installed capacity will reach 1000 GWp [23]. It can be obtained that its annual electricity generation is about 1600 TW h with the full generating hours of 1600 h, which is equivalent to 646.4 Mtce.

3.2.2. Solar thermal systems

In rural area, solar energy is mainly used as household energy, including solar water heaters, solar heating buildings and solar cookers. All of them could produce energy with near zero carbon emissions.

Based on the China Statistical Yearbook of 2011 [25], there are 703.99 million people living in rural area, and about 227.09 million households at the end of 2008. The aperture area of a solar water heater is about 3 m^2, here we take 3 m^2 per water heater to calculate. According to the data by professional committee of China's Rural Energy Industry Association of Solar Rhermal Utilization, coal consumption by water heater per m^2 is about 150–180 kg per year [27], and we take the minimum (150 kg per year) to calculate. Additionally, through calculation, we draw a conclusion that the solar heating buildings will reduce 30 kg of standard coal per m^2 a year [28], and one million solar cookers can reduce 0.3 Mt of standard coal a year [29]. The development potential of solar thermal systems is shown in Table 8.

3.3. The potentiality of geothermal energy

The development potential of geothermal energy resources in China accounts for about 8% of the total in the world, while it is still largely undeveloped [30]. Geothermal energy resources in China mainly include three types: high temperature convective type, medium and low temperature convective type geothermal energy resource, and medium and low temperature conductive type [30].The utilization of geothermal energy resources can be

divided into geothermal power generation and direct utilization. Geothermal power generation in China has a potential installed capacity of about 6 GW [30]. According to the China's famous geothermal plant reported in [31], Yangbajing Geothermal Power Plant, whose installed capacity and annual electricity production are 2.418 MW and 109.7 GW h, respectively, it can be estimated that the annual utilization hours of geothermal power is about 4537 h (109.7×10^3 MW h/2.418 MW). Thus it can be calculated that the total potential annual geothermal power production in China is up to 27.22 TW h (6 GW $\times$ 4537 h), and its net energy-saving is equivalent to 10.1 Mtce, namely it will reduce CO_2 emissions by 25.2 Mt. Ground source heat bump is a primary technology for direct utilization of geothermal energy. As estimated preliminarily, China's utilizable shallow geothermal energy each year is 356 Mtce. Deducting the energy consumption used for early exploitation, it can save energy by 248 Mtce and reduce CO_2 emission by 618 Mt.

Energy consumption of urban residents in China is 2.5 times as the rural residents, namely the rural energy consumption accounts for two-sevenths of total national energy consumption. In accordance with the proportion, we calculate the available consumption and CO_2 emissions reductions potential of geothermal resources in rural China. In rural area, geothermal power generation is able to save energy by 2.89 Mtce per year, and reduce CO_2 emissions of 7.20 Mt. Ground source heat pump is able to save energy of 70.86 Mtce, and reduce CO_2 emissions of 177 Mt.

3.4. The potentiality of wind energy

The assessment method of China's wind energy reserves that gets the identity of most scholars has been proposed [32]. This evaluation method draws the average wind power density profile through meteorological data to estimate the wind energy reserves throughout the country. According to the wind power capacity of every province, it is concluded that China's wind power reserves (based on the wind data above ground 10 m height) can reach 3.23 TW [32].

Off-grid wind power generators have priority to develop in rural areas, and the cultivated land is located as the center for construction. The western China possesses vast territory and the exploitable wind resources are also very abundant. The characteristic of the useful life of cultivated land determines that the available wind resources are only in the farming area or close to the range of farming area. Therefore, the farming wind resources are taken as the rural available wind power resources in this paper. The following shows the calculation steps. The first step is to divide the national annual average wind power density profile into various lines such as 10, 25, 50, 100, and 200 W/m^2. Considering a unit sectional area (such as 1 m^2) of the wind energy conversion device, the wind must be approved to restore the original speed by the distance about 10 times than the diameter. So in 1 km^2 range, only $10^6/100 = 10^4$ wind generators can be installed. For a area of S (unit: m^2), with average wind energy density of D (unit: W/m^2), the wind power capacity of R can be estimated: $R = DS/100$ (unit: W). In this paper, the wind energy density is divided into six levels: <10, 10–25, 25–50, 50–100, 100–200, >200 W/m^2 to estimate the cultivated land area S_i of every province, and then multiplied by the representative value D_i of each wind energy density level respectively ($R = \sum D_i S_i / 100$) to calculate each provincial wind power reserves capacity in rural area. The rural farming area and its proportion in China's total area are taken from literature [33]. According to the above method, it can be concluded that the installed wind-power capacity for available wind resources in rural China is approximately 30.56 GW and expected annual energy output of 108.16 Mtce (30.56 GW $\times$ 8760 h $\times$ 0.404 $\times$ 10^{-3} Mtce/GW h), contributing to 266.95 Mt of CO_2 emissions reductions.

3.5. The potentiality of small hydropower

In China, the small hydropower is defined as the small or micro hydropower whose capacity is less than 50 MW (including 50 MW). According to the preliminary statistics, the potential of small hydropower resources is about 160 GW, which is equivalent to an annual generation of 1300 TW h, and the actual exploitation amount of small hydropower resources is about 128 GW. The small hydropower has great potential for development, which is extensively distributed in more than 1600 mountain counties, especially in the rural areas and remote mountain areas where are suitable for small hydropower development [34].

Based on the data resources derived from the China Renewable Energy Development Strategy Workshop [35], the installed capacity of China's rural small hydropower resources under technical exploitation can reach 71.87 GW, and the annual energy

Table 9
Development potential of small hydropower resources in rural China. Installed capacity data taken from [34].

Province	Installed capacity (MW)	Annual electricity production		Province	Installed capacity (MW)	Annual electricity generation	
		Electricity (TWh)	Converted into standard coal (Mtce)			Electricity (10^2 GWh)	Converted into standard coal (Mtce)
Beijing	90.0	7.88	0.32	Hubei	4036.0	353.55	14.28
Hebei	939.3	82.28	3.32	Hunan	4146.0	363.18	14.67
Shanxi	581.0	50.89	2.06	Guangdong	4166.0	364.94	14.74
Inner Mongolia	387.0	33.90	1.37	Guangxi	2322.0	203.40	8.22
Liaoning	429.1	37.58	1.52	Hainan	397.0	34.77	1.40
Jilin	1887.9	165.38	6.68	Sichuan	5878.0	514.91	20.80
Heilongjiang	728.0	63.77	2.58	Guizhou	2554.0	223.73	9.04
Jiangsu	112.0	9.81	0.40	Yunnan	10250.0	897.90	36.28
Zhejiang	3226.5	282.64	11.42	Xizang	16000.0	1401.60	56.62
Anhui	684.5	59.96	2.42	Shanxi	1569.0	137.44	5.55
Fujian	3594.0	314.83	12.72	Gansu	1089.0	95.39	3.85
Jiangxi	3083.3	270.09	10.91	Qinghai	2000.0	175.20	7.08
Shandong	215.0	18.83	0.76	Ningxia	23.0	2.01	0.08
Henan	1031.0	90.31	3.65	Xinjiang	3979.0	348.56	14.08
				Total	71870.0	6604.73	266.83

production is 660.47 TW h, which can be converted into 266.83 Mtce (Table 9), reducing CO_2 emissions about 665.07 Mt.

Table 9 Development potential of small hydropower resources in rural China. Installed capacity data taken from [34].

4. Cost-effectiveness analysis for renewable energy source

4.1. Cost-effectiveness of biomass energy

4.1.1. Cost-effectiveness of biogas

(1) Calculation of emissions reductions

Biogas itself will produce large quantities of CO_2 emissions during the process of usage. Hence, the emissions reductions by using biogas can be considered as the emissions difference between the saved standard coal and biogas itself. Biogas is mainly used as the resident energy, and the direct combustion method is usually applied to get energy from it. Therefore, the CO_2 emissions from biogas can be expressed by

$$C_{BG} = F_{BG} B_G \tag{1}$$

where C_{BG} is CO_2 emissions from biogas, t; F_{BG} is the emission factor of biogas, $F_{BG} = 11.720\ t(CO_2)/10^4\ m^3$; and B_G is the biogas consumption, $10^4\ m^3$.

From the above analysis we can know that $B_G = 1.500 \times 10^{11}\ m^3$, equaling to 107.1 Mtce. Thus, it can be obtained that $C_{BG} = 175.80$ Mt.

According to experts statisticing, we get that it will produce 2.4925 kg CO_2 when burning 1 kg standard coal.

$$C_{coal} = F_{coal} B_{coal} \tag{2}$$

where C_{coal} is CO_2 emissions of standard coal, t; F_{coal} is the emission factor of standard coal, $F_{coal} = 2.4925$ tCO_2/tce; B_{coal} is the standard coal consumption, tce.

From the foregoing, we can calculate that $C_{coal} = 266.95$ Mt. That is to say, it would reduce CO_2 emissions of 91.15 Mt by using biogas as a substitute for standard coal.

(2) Costing of biogas

There are different specifications (6 m^3, 8 m^3, and 10 m^3) of the current biogas tanks, most of which are 8 m^3, and we take the biogas tank of 8 m^3 for calculation here.

The cost of a biogas tank mainly includes construction cost and management cost. Construction cost is mainly composed of material expense, labor costs, and its associated equipment fee. According to the current price level and statistics analysis, the average of one-time construction cost is about 1600 RMB, and the management cost of one biogas tank is around 300 RMB per year. The using life of biogas tank could be up to 15 yr, therefore the cost of an 8 m^3 biogas tank is about 406 RMB per year. The annual biogas output of an 8 m^3 biogas tank amounts to 400 m^3. Therefore, the potential for rural biogas development is about 1500 m^3 per year, namely rural China can build 8 m^3 biogas tanks about 375 million with total cost of 152.25 billion RMB. From the above we can get that the biogas produced in rural China can replace 107.1 Mtce and reduce 91.15 Mt of CO_2 emissions, so the emission reduction cost of biogas is 1670 RMB/tCO_2, and the cost of fossil fuel alternatives is 1421 RMB/tce.

4.1.2. Cost-effectiveness of bio-liquid fuel

(1) Calculation of emission reduction

We take biodiesel fuel as a representative of the bio-liquid fuel in this study. The emission factor and calorific value of biodiesel fuel is 2.96×10^{-4} kg CO_2/kcal and 9600 kcal/kg, respectively. In other words, the CO_2 emissions coefficient of biodiesel fuel can be converted to 2.84 tCO_2/t.

$$C_{BD} = 2.84 B_D \tag{3}$$

where C_{BD} is the CO_2 emissions from the combustion of biodiesel fuel, t; B_D is the consumption of biodiesel fuel, t.

Rural China's annual potential production of bio-liquid fuel is about 50 Mt, so C_{BD} equals to 142 Mt.

Bio-liquid fuel can be used as alternative fuels of oil, and CO_2 emissions by using oil can be calculated as Eq. (4)

$$C_{oil} = F_{oil} B_{oil} \tag{4}$$

where C_{oil} is CO_2 emissions of using oil, t; F_{oil} is the emission factor of oil, $F_{oil} = 2.042$ tCO_2/tce; B_{oil} is the consumption of standard coal that converted by oil, tce.

50 Mt of bio-liquid fuel can replace oil by 70 Mtce, so C_{oil} is 142.94 Mt.

The CO_2 emissions reductions by using bio-liquid fuel can be considered as the CO_2 emissions difference between the saved oil C_{oil} and bio-liquid fuel C_{BD} itself. Hence, the CO_2 emission reduction is about 1 Mt by using bio-liquid fuel.

(2) Costing of bio-liquid fuel

By initial statistics, rural China's bio-liquid fuel cost is about 4000 RMB/t at present. Rural China's annual potential production of bio-liquid fuel is 50 Mt, equaling to oil of 70 Mtce and reducing CO_2 emission per Mt. Therefore, the emission reduction cost of bio-liquid fuel is 200,000 RMB/tCO_2, and the cost of fossil fuel alternatives is 2857 RMB/tce.

Table 10
Cost of per unit emission reduction and energy saving.

Equipment	Cost	Lifetime/a	Cost of emission reduction, RMB/t(CO_2)	Cost of energy saving, RMB/tce
Solar cooker	200 RMB/unit	10	3	6
Solar heating building	300 RMB/m^2	30	134	334
Solar water heater	3000 RMB/m^2	15	535	1333

4.1.3. Cost-effectiveness of biomass power generation

Biomass power generation in rural China, with an annual production of 182.4 TWh, and with a conservative estimation, it can reduce 121.6 Mt of CO_2 emissions per year.

Through surveys and statistics, the average electricity generation cost of biomass power generation is about 0.7 RMB/kWh. Rural China's annual potential production of biomass power generation is 182.4 TWh, equaling to 73.69 Mtce. And the effect of CO_2 emission reduction by biomass power generation system is about 1.04 tCO_2/MWh [36]. Consequently, it can reduce CO_2 emissions by 189.7 Mt per year through biomass power generation, and the emission reduction cost and fossil fuel alternative cost of biomass power generation is 200,000 RMB/tCO_2 and 2857 RMB/tce, respectively.

4.2. Cost-effectiveness of solar energy

4.2.1. Cost-effectiveness of solar energy using in photovoltaic systems

The average installed cost of solar PV is about 1.5 RMB/kWh [37]. The total solar PV power generation can replace about 1208 Mtce per year, which will reduce CO_2 emissions by 3012 Mt, and the annual generation capacity is expected to reach

300 TWh. Thus, the cost of cutting CO_2 emissions and saving energy will be reached 1497 RMB/t and 3723 RMB/t, respectively.

4.2.2. *Cost-effectiveness of solar thermal systems*

Based on the market price of solar energy equipment in the past year, the cost of solar water heater is about 3000 RMB/m^2, and the service life of a solar water heater is about 15 yr. Hence, it will save energy of 102.19 Mtce and reduce CO_2 emissions of 102.19 Mt per year. Similarly, the cost of a solar cooker is about 200 RMB and the lifetime is about 10 yr [27]. So it will save energy of 72.29 Mtce and reduce CO_2 emissions of 180.19 Mt per year. The cost of roof-top energy per m^2 is about 200–300 RMB, and its service life-span is assumed as 30 yr [27]. Consequently, the solar heating building can contribute CO_2 emission reduction and energy saving by 233.93 Mt and 583.06 Mtce, respectively. Based on the analysis, combining with literature [27], the cost of emission reduction and energy saving can be calculated (Table 10).

4.3. *Cost-effectiveness of wind energy*

The wind power generation cost depends on several factors such as construction cost, fuel cost, operation and maintenance cost, financial cost, production rate, operation time, and so on. The remarkable characteristic of wind power is that it has not fuel cost, so once the wind turbine is completed, its cost is relatively stable. Wind power generation cost is closely related to the following factors [38]:

(1) The unit construction cost of wind power, which is about 9000 RMB/kW in China.
(2) Operation and maintenance cost, which is about 0.12 RMB/kW h in China.

The cost of wind power is indicated by Eq. (5).

$$G = C/T + m \tag{5}$$

where G is the cost of power output per unit, RMB/kWh; C is the construction cost, RMB/kW; T is the annual generating hours, h; m is the operation and maintenance cost, RMB/kW h.

Looked at more broadly, the cost of electricity output is 1.147397 RMB/kW h. According to the development and utilization of wind power installed capacity (30.56 GW) and generating capacity ($30.56\ \text{GW} \times 8760\ \text{h} = 267.7\ \text{TW h}$) in rural China, the operation and maintenance cost of wind power generation is $3.071780106 \times 10^{11}$ RMB per year. Wind power generating could replace 108.16 Mtce and reduce 266.95 Mt of CO_2 emissions, so the costs of its CO_2 emissions reductions and fossil fuel alternatives are 1150 RMB/tCO_2 and 2840 RMB/tce, respectively.

4.4. *Cost-effectiveness of geothermal energy*

According to preliminary estimation, if we simply consider the construction and operation cost of power plants, the geothermal power generation cost in China is estimated at around 0.4 RMB/kW h. However, as an important prophase work of geothermal power generation, costs of resources prospecting and drilling are high. Taking the cost of exploration and drilling into account, geothermal power generation cost may reach about 1.0 RMB/kW h. Therefore, for geothermal generating, the unit cost of reducing CO_2 emissions and replacing fossil fuel are about 1080 RMB/tCO2 and 2692 RMB/tce, respectively.

Compared with the other modes of heating, the cost of direct utilization of geothermal energy is relatively low. Estimated primarily, under current technology, the cost of direct utilization of geothermal energy is about 0.2–0.4 RMB/kW h. Taking 0.3 RMB/kW h for calculating, the unit cost of ground source heat bump for reducing CO_2 emissions and replacing fossil fuel are 324 RMB/tCO_2 and 808 RMB/tce, respectively.

4.5. *Cost-effectiveness of small hydropower*

According to the financial general rules and financial systems, combining with the characteristics of power production enterprises, the original Ministry of Electric Power issued the actualizing opinions on the cost accounting of electric power enterprises in July 1993. It clearly determines the allowable costs of the electric power enterprises, and all of the electric power enterprises take it as the basis of electric power cost accounting at present. According to the allowable cost of power production, we can calculate the production cost of trading session under any probabilities, and part of the calculation results are shown as Table 11.

From a holistic point of view, along with the growth of load, the total production cost and variable cost are increasing, but the unit cost of electricity including unit variable cost and fixed cost is falling. According to the production cost of trading session under any power shown in literature [39], this study takes the most ideal situation (unit load is 100%) as the unit cost (142.08 RMB/MW h), namely its substitution unit fossil fuel cost is 352 RMB/tce.

Electricity production by small hydropower generation equals to 0.404 Mtce per MW h and will decrease CO_2 emissions of 0.993 Mt. Therefore, the unit emission reduction cost of small hydropower is 143 RMB/tCO_2 (142.08/0.993).

Table 12 shows the cost-efficiency of each renewable energy resource, from the results we can find that some of the renewable

Table 11
Small hydropower production cost of the trading session under any probabilities, RMB/MWh.

Unit load (%)	Total cost of production	Variable cost	Fixed cost	Unit cost	Unit variable cost	Units fixed cost
40	13388.42	7455.92	5742.72	223.08	127.39	95.69
50	14668.16	8925.44	5742.72	195.34	118.86	76.48
60	15969.33	10266.61	5742.72	177.34	113.57	63.71
70	17260.31	11517.59	5742.72	164.30	109.64	54.66
80	18440.72	12698.00	5742.72	153.66	105.81	47.85
90	19891.71	14148.99	5742.72	147.23	104.73	42.50
100	21376.94	15634.22	5742.72	142.08	103.91	38.17

Table 12
Cost-effectiveness of each renewable energy source.

Energy			Cost of per unit emission reduction, RMB/tCO_2	Cost of per unit substitute for fossil energy, RMB/tce
Biomass	Biogas		1670	1421
	Bio-liquid fuel		200,000	2857
	Biomass power generation		673	1733
	Photovoltaic		1497	3723
Solar	Solar thermal utilization	Solar stoves	3	6
		Solar house	134	334
		Solar water heater	535	1333
Geothermal	Geothermal power generation		1080	2692
	Geothermal-source heat pump		324	808
Wind			1150	2840
Small hydropower			143	352

energy such as biogas and bio-liquid fuel are energy saving, but not low carbon. Biogas, whose cost of fossil energy substitution is 1421 RMB/tce which ranks sixth only, however, its emission-reduction cost is 1670 RMB/tCO_2 which ranks second only to bio-liquid fuel. Biogas itself will produce large quantity of CO_2 emissions during the process of usage. Moreover, as the main component of biogas, methane (CH_4) is a powerful greenhouse gas 25 times more potent than CO_2 [40]. It will lead to CH_4 leakage if the quality of biogas tank has a little negligence or the combustion of biogas is incomplete, so that seriously exacerbate the greenhouse effect. Bio-liquid fuel, as an effective alternative to fossil fuel such as gasoline, kerosene and diesel, its substitution cost to fossil fuels is 2857 RMB/tce, while its emission reduction cost is as high as 200,000 RMB/tCO_2 which is 10 times more expensive than any other types of renewable energy. Consequently, under the low-carbon background, the evaluation index of the promotion and application priority of each renewable energy resource should comprehensively consider its cost of per unit emission reduction as well as fossil fuel reduction, to make the best choice for developing and exploiting the renewable energy resources. As shown in Table 12, we should give priority to the solar energy, small hydropower and direct utilization of geothermal energy for the promotion and application of renewable energy.

5. Conclusions

The development of renewable energy as well as its potential for reducing CO_2 emissions in rural China is discussed. Based on the above analysis, the crucial outcomes of this study could be summarized by the following: (1) the theoretical potential of renewable energy in rural China is up to 2251 Mtce under ideal conditions (technology and economy are affordable enough); (2) carbon-free energy resources such as solar, geothermal, wind and small hydropower can reach 2000 Mtce theoretically, namely 100% even 2.2 times of the total rural energy consumption in China below 2008 levels can be affordable, achieving zero carbon emissions; (3) biogas and bio-liquid fuel are energy saving, but not low carbon, thus, in certain cases, we can consider to give priority to the solar energy, small hydropower and direct utilization of geothermal energy.

Mention should be made of that the development of renewable energy can reduce the CO_2 emissions in rural China greatly. Though it has obtained certain achievements, there still exist some challenges, such as technology shortcomings, economic barriers, policy defects. To promote the renewable energy further in rural China, more work need to be done. The rural renewable energy resources usually need to be exploited and used locally for they cannot be transmitted over long distances. Consequently, the rural energy policy should be suited to local conditions, making scientific planning and rational distribution for the local rural energy. However, the Chinese government has not yet issued a separate document which is aimed at the rural energy construction so far, and the relevant energy policies are usually focus only at the province or central level. In short, the rural energy policies should be made down to the district and county as the following:

(1) Have a deeper understanding of the strategic position of rural energy construction and then determine the development focus and scale.
(2) Make a better development plan for rural renewable energy on the basis of resource surveying and planning, as well as the different conditions such as the local geographic and economic conditions, resource advantage, the requirements and characteristics of energy, conditions of natural climate and economy, the situation of energy supply-demand balance, and so on.
(3) Develop a reasonable rural energy production consumption pattern.

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